Hydrobiologia (2005) 550:221–235
P. Viaroli, M. Mistri, M. Troussellier, S. Guerzoni & A.C. Cardoso (eds),
Structure, Functions and Ecosystem Alterations in Southern European Coastal Lagoons
DOI 10.1007/s10750-005-4382-0

Aquatic birds as bioindicators of trophic changes and ecosystem deterioration in the Mar Menor lagoon (SE Spain)

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Key words: dynamic model, Mar Menor, nutrient flows, irrigated lands, aquatic birds, bioindicators

Abstract

The Mar Menor is the largest coastal lagoon in the Western Mediterranean and it is an important site for wintering and breeding waterfowl. During recent decades several hydrological and land-use changes in the watershed have increasingly threatened the conservation of the lagoon due to the development of urban areas, tourism and agriculture. A dynamic system model has been developed at the watershed scale to estimate the annual load of nutrients reaching the Mar Menor-associated wetlands. At present, mean annual loadings of approximately 2000 tonnes of nitrogen and 60 tonnes of phosphorus are delivered to the lagoon. The simulation results emphasize the role of heavy rainfall events and floods in the formation of the total nutrient load. The composition of aquatic bird communities has been used to assess the nutrient impact on the lagoon food-web. The Great Crested Grebe is apparently the species most closely dependant on local trophic conditions. The related Black-necked Grebe, that dominates the waterbird community of the lagoon, plays a similar role, but its more opportunistic response to changes in food resources, reduces its indicator value. The abundance of the two species of grebes seems to closely track the nitrogen load curve, especially during the first phase of enrichment, suggesting the existence of a direct trophic relationship. In the following phase, jellyfish blooms coincide with the bird decline. Jellyfishes seem to have a buffering effect towards nutrients, determining a bottom up limitation to other trophic compartments. In recent years, this buffering capacity has probably been overloaded, favouring the growth of new food resources available to the grebes. Unlike grebes, *Mergus serrator*, a typical piscivorous bird, does not seem to be affected positively by eutrophication since it shows a long-term stability in numbers or even a slight decline. Since this suspected decline would parallel a long-term reduction of fish catches, the species could be regarded as a potential indicator of habitat deterioration.

Introduction

The Mar Menor (SE Spain) is the largest coastal lagoon in the Western Mediterranean, with a 135 km^2 surface area and a 580 hm^3 volume (Fig. 1). Inside the lagoon there are five volcanic islands. The lagoon is almost closed by a sand bar 22 km long with a width varying between 100 and 1200 m. The connection with the open sea is very narrow. Dominant currents are generated by the Mediterranean water flowing throughout the natural channels called *golas* such as the Estacio and those in the Encañizadas area. The current regime through the Estacio channel is highly variable, with a frequent inversion of the direction of flows (Arévalo, 1988). After the dredging and enlargement of the Estacio channel in 1973, the total water exchange between the Mediterranean and

Figure 1. Location of the Mar Menor lagoon and its watershed.

the lagoon has increased, reaching a value around 1.6 $hm^3\ d^{-1}$, which accounted for a high turnover rate. The Mar Menor is characterized by hypersaline waters with a range between 42 and 47 psu. Water temperature varies between 10 and 32 °C (Pérez-Ruzafa et al., 2004). The phytoplankton density is usually low (Ros & Miracle, 1984). Before the enlargement of the Estacio channel, primary productivity was dominated by macrophytes, especially *Cymodocea nodosa*. Since the late 1980s, the benthic macroalga *Caulerpa prolifera* covered a considerable part of the lagoon (Pérez Ruzafa et al., 2002). When compared to other coastal lagoons, the fish community in Mar Menor is characterized by a higher species richness, with a relevant presence of threatened species, namely the sea horse (*Hippocampus guttulatus*) and the fish *Aphanius iberus*, which is included in the Annex II of the European Habitat Directive (Mas, 1996).

The Mar Menor lagoon is an important site for wintering and breeding waterfowl. Its ornithological value increases greatly when the whole surrounding wetland system is taken into account. The industrial salt ponds, and natural marshland and minor aquatic habitats are important feeding, breeding and roosting areas for flamingos, herons, waders, gulls and terns (Robledano & Esteve, 1992; Robledano, 1998; Ballesteros & Casado, 2000). The main lagoon is a well-delineated and closed water-body, which is used by some species (grebes and seaducks) in a nearly exclusive manner (Hernández & Robledano, 1997).

The typical bird guild in open waters includes fish and invertebrate feeders that exploit the water column and the benthos by diving, namely Great Crested Grebe (*Podiceps cristatus*), Black-necked Grebe (*Podiceps nigricollis*), Great Cormorant (*Phalacrocorax carbo*) and Red-breasted Merganser (*Mergus serrator*). Details on the biology, ecology, distribution, population status and trends of these species can be found in Cramp & Simmons (1978), Del Hoyo et al. (1992), Rose & Scott (1997), Delany et al. (1999), Gilissen et al. (2002), Wetlands International (2002), Martí & Del Moral (2002, 2003). The natural and ecological values of the Mar Menor lagoon and associated wetlands have been recognised and given international and national protection status, including the designation of the Mar Menor as a Ramsar Site, an Area of Special Protection for Birds and a Special Conservation Site (proposed) under the Habitat Directive and Specially Protected Area of Importance for the Mediterranean Sea, according to the Barcelona Agreement.

In the last two decades, several hydrological and land-use changes occurred in the Mar Menor watershed, which are threatening the Mar Menor conservation. The development of urban areas and tourism, and the intensification of agriculture are among the main pressures. The Mar Menor watershed is a 1200 km^2 plain slightly inclined towards the lagoon and drained by several ephemeral channels (ramblas). It is predominantly exploited for agricultural uses. The Tagus-Segura water transfer system, which opened in 1979, favoured a significant increase of irrigated lands, which led to changes in the hydrological dynamics of the watershed and in the nutrient loads delivered to the lagoon and associated wetlands. As a consequence, the lagoon has changed from moderately oligotrophic to relatively eutrophic (Pérez Ruzafa et al., 2002). The nitrate concentration in the water has increased by one magnitude order with respect to the typical values which were detected ten years ago (Pérez-Ruzafa & Marcos, 2004). This has favoured the growth of larger phytoplankton cells and changes in the trophic structure, with high densities of bigger diatoms such as *Coscinodiscus* spp. and *Asterionella* spp. (Pérez Ruzafa et al., 2002).

In the mid 1980s, after the enlargement of the Estacio channel, two allochtonous species of jellyfish (*Rhizostoma pulmo* and *Cotylorhiza tuberculata*) were observed in the lagoon. Due to temperature and salinity conditions, these species closed their biological cycle inside the lagoon (Pérez Ruzafa & Aragon, 2003). A decade later, the jellyfish blooms started in response to the increased nutrient inflow and lagoon eutrophication (Pérez Ruzafa & Marcos, 2004). Although the jellyfish blooms can also depend upon the overfishing of their predators or global warming (Arai, 2001; Mills, 2001), in the mar Menor the nutrient loading and inherent eutrophication processes seem to be the most probable cause of their successful deveopment. Jellyfish populations are the main top-down agent in the Mar Menor, controlling eutrophication processes (Pérez Ruzafa et al., 2002). The control over the food web is carried out both through the direct use of nutrients by the endosymbiotic zooxantelas of *C. tuberculata* and through direct predation on plankton (Pérez Ruzafa & Aragón, 2003). The summer proliferation of the two allochtonous species of jellyfish, started during mid 1990s, with mean densities of 0.45 and 2 individuals per 100 m^3 respectively in 1997, local maximum densities of 40 individuals per 100 m^3 and a total population of 46 million of individuals in summer (Pérez-Ruzafa et al., 2002), constitutes an important symptom of the ecological changes affecting the lagoon. These jellyfish blooms not only have environmental but also socio-economic effects due to their impact on the quality of bathing water and, therefore, on the tourist activities in the Mar Menor.

The management of coastal water quality has shifted from an initial focus on point sources to the need for reducing non-point pollution, which is mainly of agricultural origin (David et al., 1997; Meissner et al., 2002). Therefore, the efforts to estimate the net nutrient loads reaching coastal areas through modelling at a watershed scale have increased in the last years (Arhonditsis et al., 2000; La Jeunesse et al., 2002; Payraudeau et al., 2003). Models are necessary especially in the case of large areas, insufficient or inadequate data and complex watersheds. In the case of the Mar Menor watershed, all these factors are present: the watershed is wide, a complex set of socio-economic and environmental factors drives the loading of nutrients into the lagoon, data on the hydraulic loading are almost absent and data on water quality are scarce. In this respect, we have developed a dynamic system model to estimate the annual load of nutrients reaching the lagoon and the associated wetlands. The dynamic system model takes into account the load of nutrients originating in the urban and agricultural land sector, the latter being the most important source of nutrients, as in other agricultural watersheds (Jordan et al., 1997; Meissner et al., 2002).

Aquatic birds, especially grebes, have been identified as indicators of water eutrophication processes (Rutschke, 1987), since they show a positive response to the first stages of nutrient enrichment. At a country or regional scale, these processes have usually been cited when interpreting waterbird population trends (Fuller, 1982; Nilsoon, 1985; Ferrer et al., 1986; European Environmental Agency, 2000). However, among landscape managers, very little attention has been paid to the warning potential of waterbirds with respect to environmental changes within a local or regional context. Moreover, wildlife managers show a greater concern about general bird figures, as a gross indicator of 'good management', than about the particular meaning of individual species as wetland quality indicators. In some cases, waterbird censuses have become a routine that lacks the scientific and administrative support and the resources needed to guarantee standardized, useful data.

In this paper, the agricultural loads of nutrients and their effects on aquatic birds in the Mar Menor lagoon are presented and discussed. The hypothesis that the typical lagoon species can respond to altered nutrient inputs is also assessed in order to use birds as indicators of the aquatic environment quality.

Materials and methods

Dynamic simulation model

Dynamic system models describe the structure of a system by reference to the main factors, interactions and feedback processes which simulate its dynamic behaviour (Forrester, 1975; Roberts et al., 1983; Barlas, 1996; Wolstenholme, 2003). The structure is defined by a set of variables, basically levels and rates, and by the relationships and feedback loops they establish. Dynamic system models are very useful for studying and understanding complex systems and have been extensively applied to biological and environmental systems (Hannon & Ruth, 1997; Ford, 1999). The dynamic model we propose was developed using VENSIM software (Ventana Systems, 1998).

The aggregated watershed model focuses on an estimation of the nutrient inputs reaching the Mar Menor lagoon-associated wetlands complex and takes into account the relevant environmental and socio-economic factors and feedbacks driving the land use changes and the load of nutrients. The model considers endogenous factors, such as the rate of increase in irrigated lands and the amount of nutrients which are mobilised in the watershed, and exogenous factors, such as big rainfall events.

Model parameters were obtained making use of the bibliography, callibration procedures and the available empirical data for the Mar Menor watershed, regarding the fertiliser inputs and leaching coefficients and the available nitrogen and phosphorus content in watercourses. The fertiliser inputs and leaching coefficients are close to the values found in other intensive Mediterranean irrigated lands (Guimerà & Candela, 1994; Guimerà et al., 1995; Moreno et al., 1996; López Gálvez & Naredo, 1996). Although data on water amount and quality in watercourses reaching the lagoon are very scarce, the existing information has allowed a first estimation of the overall retention coefficient of N and P at watershed scale, since empirical values are not available. As in other aggregated models about export of nutrients at watershed scale, mean rainfall values and actual data series have been used to estimate the effect of heavy rainfall events on the residence time and on the retention coefficient of nutrients at basin scale (Paaby et al., 1995). Model validation will be carried out as long as the required measured data are available. Additional details on model description can be found in Martínez Fernández & Esteve Selma (2000).

Aquatic birds

The indicator value of birds with respect to changes in the hydrochemical and trophic status of the wetland system was assessed by using January counts of waterbirds, undertaken as part of the International Waterbird Census (IWC) scheme. Linear regression analysis of the wintering populations versus the estimated agricultural loadings of N to the wetland was used. For each individual species we used the number of birds counted in the lagoon as response variable and the estimated nutrient load as explanatory variable. The analysis were performed using the R software suite (*www.r-project.org*). Bird data were previously normalized using $\log[n + 1]$. For the reasons already explained, we restricted the analysis to the counts of typical species of open waters (*Podicipedidae*, *Phalacrocoracidae* and *Mergus serrator*). Moreover, this is the group of aquatic birds for which the most complete set of counts is available, with 23 censuses from 1972 to 2002. Counts of these species were made within winter waterfowl census scheme, which has been in operation in the Mar Menor since 1972.

The Mar Menor census has been performed along a predefined boat route inside the lagoon (for details see Hernández & Robledano, 1997). Coverage for each species is variable, depending on their visibility and, in turn, related to size and behaviour. For the smaller Black-necked grebes (*Podiceps nigricollis*), it has been estimated that counts should be multiplied at least by two to obtain a whole lagoon figure (Hernández & Robledano, 1997). For other species, censuses are assumed to cover the whole lagoon population, provided that no census has been made under unfavourable weather conditions, and assuming that no double counting has occurred.

Since the changes in bird abundance could also result from external factors, affecting the population at other scales, we compared the local trends in waterbird abundance with those shown by national and global (flyway or region) populations (see references above). National trends (1980–2001) have been presented in a recently published compilation of Spanish waterbird censuses (Martí & Del Moral, 2002). This work uses interannual indices calculated with the software used by Wetlands International for trend analysis of waterbird monitoring data (Delany et al., 1999). The Spanish census compilation includes also a database of censuses, from which numerical trends have been represented and compared with the Mar Menor lagoon census (using raw data); unfortunately only data from 1990 to 2001 are available for this comparison.

Results

Figure 2 shows a simplified diagram of the agricultural sector of the dynamic system model of nutrient loads from the watershed. The dynamic model simulates the land use changes generated by the Tagus-Segura water transfer, the increase in the area occupied by greenhouses and open-air horticultural crops and the consequent increase in the nutrient load reaching the lagoon-associated wetlands complex, depending on the interaction between the nitrogen and phosphorous mobilisation in the watershed and the rainfall regime, especially the existence of big rainfall events. The dynamic model also takes into account the load of nutrients through the salty wastewater coming from the desalination plants installed in the Mar Menor watershed to desalinate the groundwater. This salty wastewater presents high concentrations of nitrogen due to the heavy groundwater pollution, with average values of nitrate greater than 100 mg l^{-1} in the areas of the Quaternary aquifer close to the lagoon and maximum values reaching 300 mg l^{-1} (Pérez Ruzafa & Aragón, 2003).

Since 1979, the Tagus-Segura water transfer resulted in an accelerated increase in the total area occupied by irrigated lands, as shown by the historical data series (Dirección General de Producción Agraria, 1998) and the simulation results (Fig. 3). Total irrigated lands reached an area of 330 km^2 at the end of the simulated period. Moreover, greenhouses, which result in a fertiliser input doubles that of open-air horticultural crops, have increased at a higher rate.

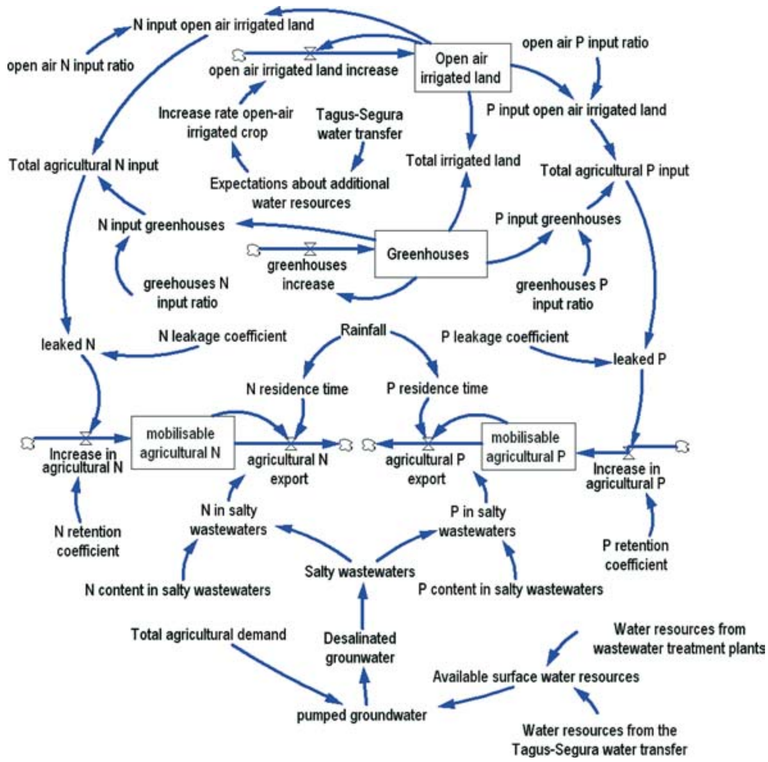

Figure 2. Simplified diagram of the watershed model.

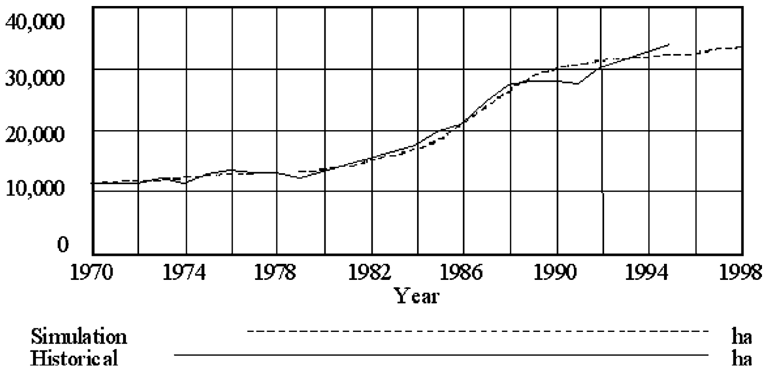

Figure 3. Total irrigated land in Mar Menor watershed. Historical and simulated data series.

New irrigated lands, characterized by a very intensive use of fertilisers, are created at the expense of dry-lands, characterized by a low ratio of fertiliser input. As a result, model simulation shows a significant increase during the last two decades in the estimated nitrogen and phosphorus load reaching the Mar Menor lagoon and the associated wetlands complex. As shown in Figure 4, model simulation resulted in 2000 tonnes of nitrogen and 60 tonnes of phosphorus per year.

The lack of empirical data does not allow a direct comparison with these estimated values. The absence of permanent rivers and the complexity of the hydrological response of the network of ephemeral channels under a torrential rainfall regime have probably contributed to this scarcity of field data on water discharges. However, the high values of estimated nitrate and phosphorous load obtained with the dynamic model agree with the scarce measured data on nitrogen and phosphorus concentration of several flows in the Mar Menor watershed. All these flows show high nitrogen contents, with values of approximately 62 mg l^{-1} in the Albujón ephemeral channel, 160 mg l^{-1} in some drainage channels and 85 mg l^{-1} in salty wastewaters from desalination plants (Martínez Fernández & Esteve Selma, 2003).

As in other Mediterranean watersheds, heavy rainfall events and floods play a major role (David et al., 1997; Xue et al., 1998), leading to the mobilization and loading of important stocks of nutrients stored in the watershed during months or

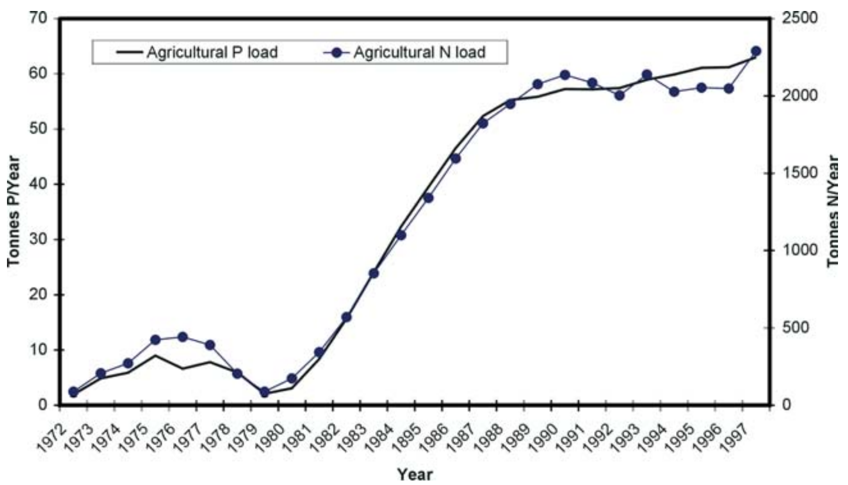

Figure 4. Estimated agricultural loads of nitrogen and phosphorus to the Mar Menor-associated wetlands complex from the Mar Menor watershed, as shown by model simulations. Mean annual values.

years, especially in the case of nitrogen because of its higher mobility. As a result, high monthly fluctuations in the nutrient flowing into the Mar Menor lagoon-associated wetlands complex are expected, depending on the rainfall regime. The simulation results of the present dynamic model at a more detailed temporal resolution (Fig. 5) shows the high monthly variability of estimated load of nitrogen. Besides the existence of heavy rainfall events, other factors are involved in such fluctuations, especially the previous rainfall regime and the accumulated pool of mobilisable nitrogen and phosphorus in the watershed, generating delays and other dynamic effects, as shown in other studies (David et al., 1997; Knappe et al., 2002). Heavy rainfall events and floods represent a significant proportion of the estimated total water and nutrient flows. Big rainfall events typically occur in Autumn. The simulation run shows the effect of a big flood occurring in November 1997, when the estimated nitrogen load increased almost three times compared to base data.

The increased nutrient concentration associated to high densities of large phytoplankton cells, and the top-down control carried out by jellyfish (Pérez Ruzafa et al., 2002) is also favouring other indirect environmental changes, such as those observed in aquatic birds. There has been a general increase in the number of three wintering species, namely the two grebes and the Great Cormorant, although the patterns are somewhat different (Figs. 6 and 7). Regression analysis indicate that the estimated nitrogen input is a good predictor of the abundance of these waterbirds, especially in the case of the Great Cormorant and the Black-necked Grebe. Both *Podiceps cristatus* and *nigricollis* increased in numbers mainly between 1984 and 1995. Afterwards, the record is less complete, but both species numbers seem to decrease and to become more variable. Peak records of 398 wintering Great Crested Grebes and 924 Black-necked Grebes in the winter of 2003 (unpublished data) confirm that the overall trend is still positive for these two species.

The linear regression models and the original data points for the four waterbird species, plotted against nutrient input estimates are reported in Figure 8. Although, they respond positively to the increased nutrient load, some discrepancies emerge, particularly in the region between 2000 and 2500 tonnes of nitrogen. Moreover, it is possible that these trends are a result of changes of national- or flyway-level populations. When local census trends are compared with the Spanish data set (Martí & Del Moral, 2002) or with international waterbird censuses (see references above), most species show similar positive trends both at a national and international scale, but the patterns of increase are non always concordant.

Wintering *Podiceps cristatus* increased in Spain by a factor of 15 from 1980 to 2001 (Martí & Del Moral, 2002). The same authors calculate that for Eastern Spain, Mar Menor lagoon included, the increase is only 2.5. The Mar Menor lagoon holds on average a 2.6% of the Spanish population. Our data from 1979 to 2003 show how the population

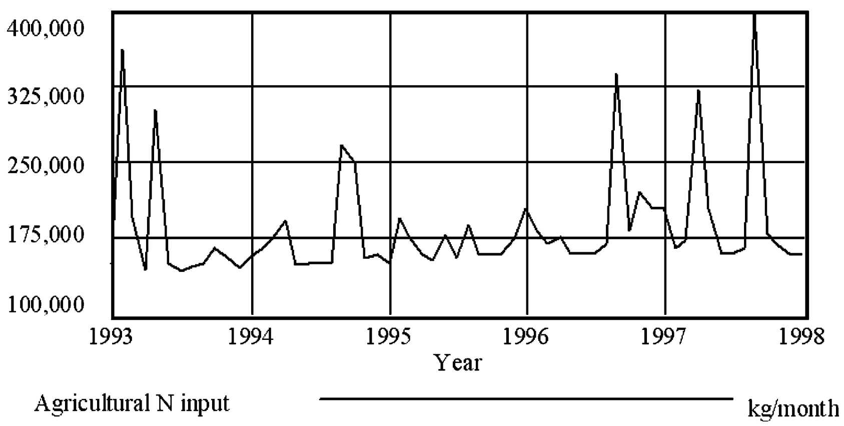

Figure 5. Monthly variability of agricultural nitrogen load, showing the effects of rainfall events.

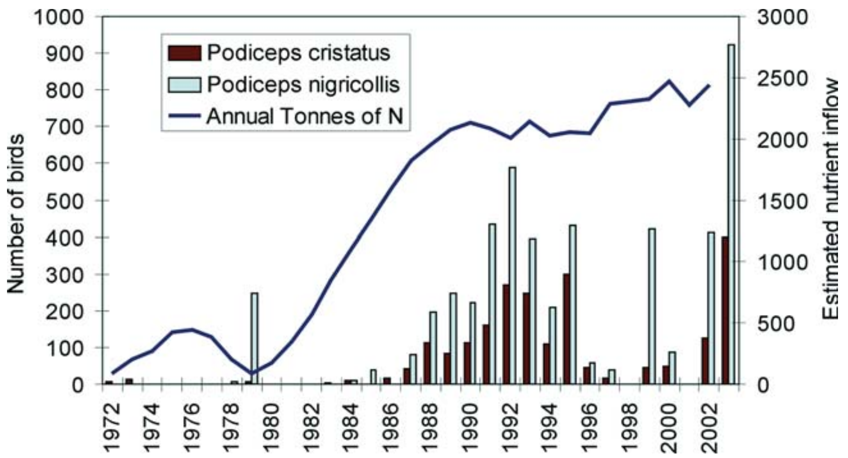

Figure 6. Changes in the number of Great Crested Grebes and Black-Necked Grebes wintering in the Mar Menor lagoon. Data from January waterbird census of 1972–2003, not available for 1974, 1976–77, 1980–82, 1998 and 2001. The estimated nitrogen input is also represented (solid line).

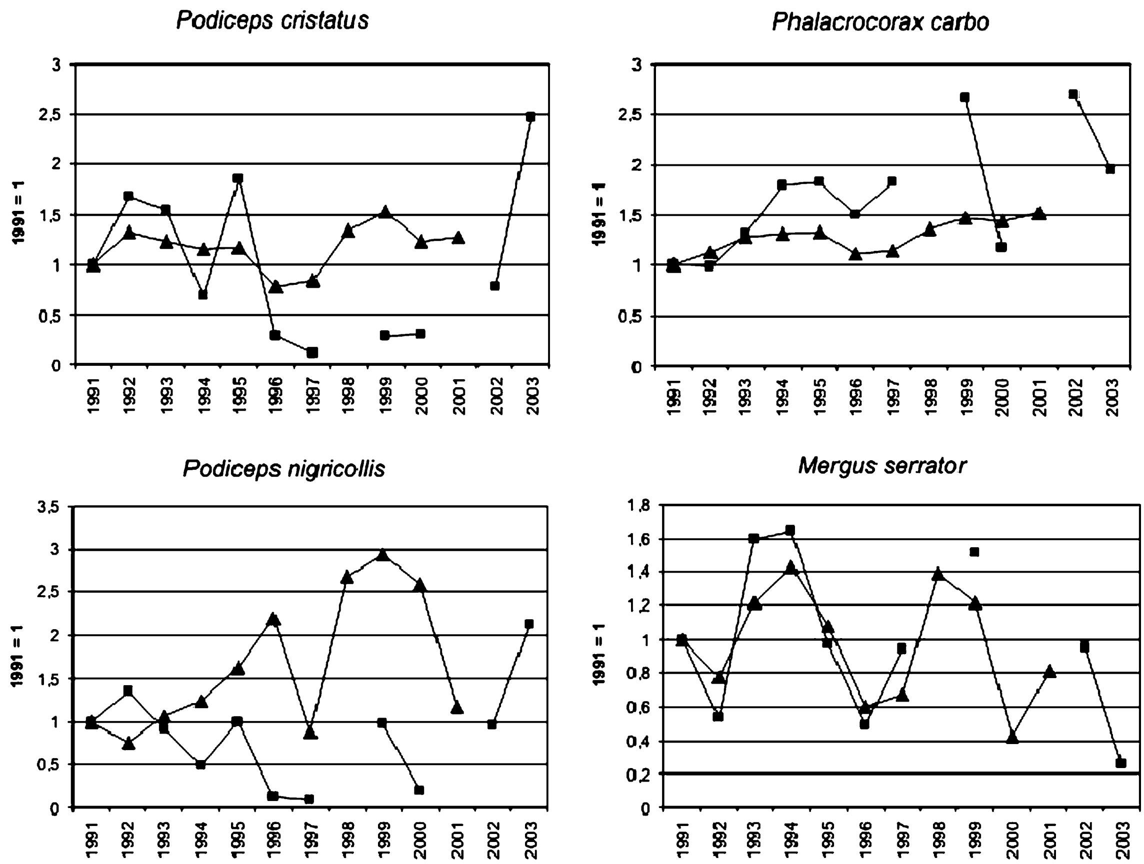

Figure 7. Trends in the numbers of the four main wintering species in the Mar Menor lagoon (January census), and of the Spanish populations of the same species, expressed as a factor of the initial year, for the period 1991–2003. Triangles: Spanish data, Squares: Mar Menor Lagoon Data.

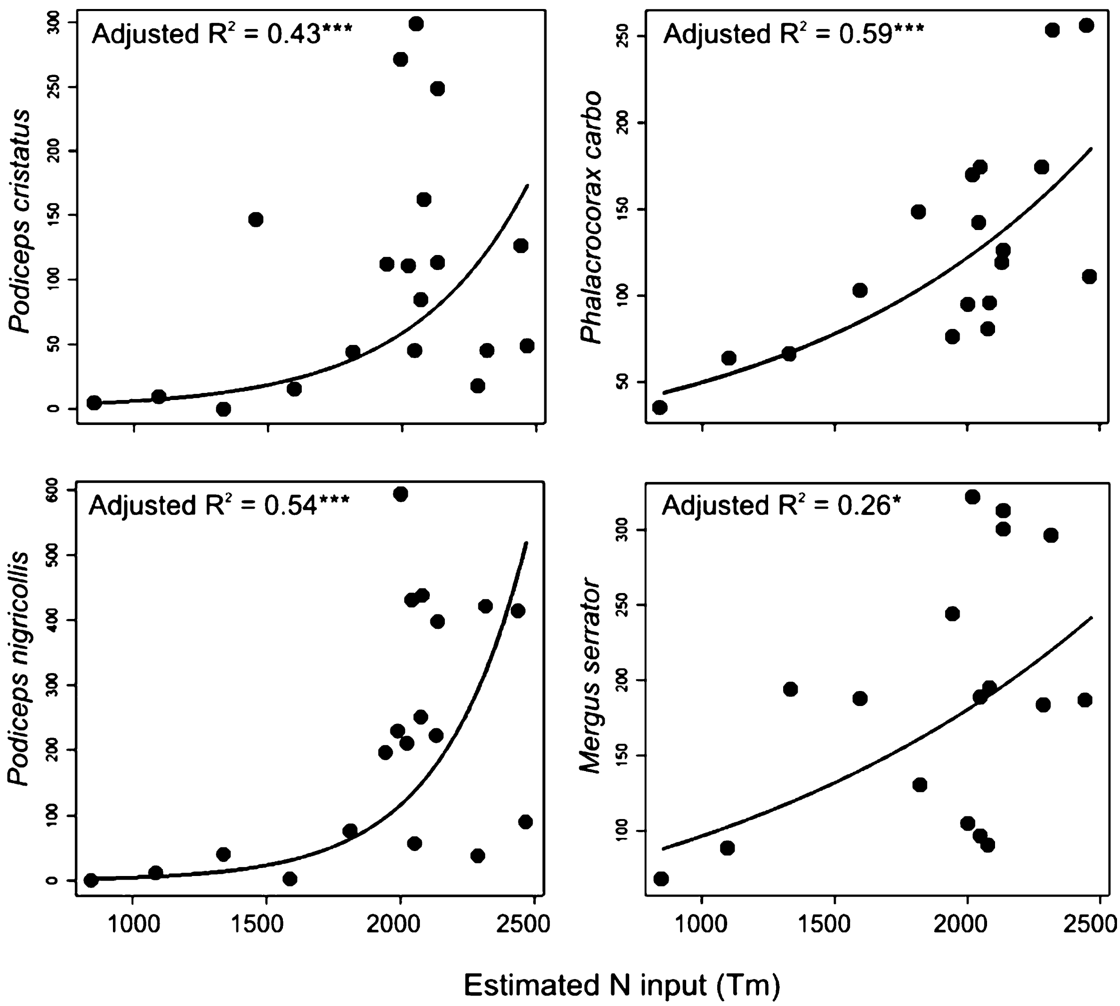

Figure 8. Plots of the linear regression models, plus the original data points for the census of waterbird species (number of individuals), against the nutrient input estimates (tonnes of *N*). Adjusted R^2 and significance level of *p*-values are also shown (***$p < 0.001$; **$p < 0.01$; *$p < 0.05$).

increased by up to 40 times in 1994, and even more in 2003, although the intervening years show a decline. This trend is difficult to explain by only considering the general increase in wintering populations, also noticed at an European scale (Adriaensen *et al.*, 1993). Moreover, the comparison of trends for the last decade of the 20th century, with the same reference year (1991), shows a very different pattern of increase. The steady increase of the Spanish population contrasts with the partial decline of the Mar Menor figures after 1995. The same does not apply for *Podiceps nigricollis*, despite its closer relationship with the estimated nitrogen load. The pattern of general increase and recent fluctuation is characteristic of both the national and Mar Menor count data, making it difficult to discriminate between general and local influences. At a national scale the wintering population increased more than 15 times between 1980 and 2001, while the numbers of birds wintering in eastern Spain increased less than 5 times, a change similar to that shown by our Mar Menor data. The lagoon contributes 5.9% to the Spanish population (Martí & Del Moral, 2002). When 1991 is used as reference year, however, the Spanish and local trends look almost inverse, suggesting that the patterns of change are responding to different factors (Fig. 7).

Phalacrocorax carbo shows a clear increasing trend similar to that of the Spanish population as a whole, which has grown by a factor of less than 10. The same applies to the eastern Spanish population of which the Mar Menor is a contributing site (Martí & Del Moral, 2002). This is also reflected in the similitude of the 1991–2000 national and local trends (Fig. 7). Moreover, the increase in the European population of cormorants is well-established (Van Eerden & Gregersen, 1995; Rose & Scott, 1997; Wetlands International, 2002), suggesting common explanatory factors.

The census figures of *Mergus serrator* show the weakest relationship with the estimated nutrient input, although the regression model suggests some positive response. This duck is one of the most representative species of the lagoon, usually the main site for this species in Spain (Hérnández & Robledano, 1997; Martí & Del Moral, 2002). Census of this species in the Mediterranean showed an increase of 43% between 1970/1975 and 1989 (Van Vessem et al., 1992), and in general it is considered an increasing species in Europe (Wetlands International, 2002). However, when 1991 is used as reference year, data for the subsequent decade show a negative, parallel trend, both at a national and local level.

Discussion

Model estimation of nutrient loads

Trends in land-use change have a strong impact on the evolution of nutrient loads. While in the catchment of Thau lagoon (France), the main land-use change during the last 25 years has been a decrease in vineyards, which has contributed to the general reduction of phosphorus entering the lagoon (La Jeunesse et al., 2002), the Mar Menor river-basin has experienced a pronounced growth of irrigated lands. Moreover, the greatest increase has been in greenhouses, the irrigated land system with the highest fertilizers input.

Estimated values for the annual nitrogen and phosphorus load in the Mar Menor watershed fall within the ranges obtained in other watersheds dominated by intensive agriculture (Longabucco & Rafferty, 1989; David et al., 1997; Jordan et al., 1997). Although additional data are required, these first overall estimates and trends given by the dynamic model offer a basis for understanding the main factors and processes affecting the pattern of nutrient loads and their effects on aquatic birds, as shown by the different numerical trends of the analysed species during the study period. The biological interpretation of these numerical changes suggests different degrees and types of response to local environmental changes.

Numerical trends of birds and nutrient inputs: alternative explanations

The Great Cormorant, the species showing the steadiest and most prolonged increase, is at the same time the least strictly tied to the lagoon as a feeding area, and thus a poor indicator of eutrophication at a local (lagoon) scale. It can, however, respond to this at a catchment or regional scale, as it does in other areas (e.g. HELCOM, 1996) *Phalacrocorax carbo* is highly mobile, and although many birds counted in the lagoon may be feeding inside it, individuals recorded in daily roosts can fly several kilometres to feed in the open sea or in irrigation ponds of the surrounding agricultural landscape (personal observation). The growth of the local population could be an effect of the overall increase in the European population, a response to the general increase in trophic resources (eutrophication of the whole wetland system plus the growing availability of complementary feeding habitats within a short distance), or a combination of both. At the scale of the Mar Menor watershed, there seems to be a general increase in the area of aquatic habitats, and in the food supply for waterbirds. Foraging opportunities have increased through the flooding of terrestrial areas, the eutrophication of shallow littoral waters, the creation of large numbers of irrigation ponds, the spread of marine culture and the recovery of traditional fish farms in the lagoon outlet ('encañizadas'). The colonisation and subsequent increase in breeding species like Little Egret (established recently in one of the lagoon's islands) and Gull-billed Tern (breeding in saltpans since 1995, with a population rising up to 95 pairs in 2002) are interpreted as a response to this process (Robledano et al., 2005).

Contrasting with these species, grebes, and especially the Great-crested grebe, are most probably responding directly to the increase in the lagoon's trophic resources. Although they are also piscivorous, they feed on invertebrates to a large extent. In particular, peak numbers of Black-necked Grebes in saline lagoons have been associated to explosive growths of invertebrate prey (Calvo & Robledano, 1992). Moreover, the fact that *Podiceps nigricollis* reaches its maximun abundance in El Hondo reservoir, a highly eutrophic wetland located in the nearby Alicante province (Viñals et al., 2001), 40 km North of the Mar Menor, may be another signal of the species' response to a general process of nutrient enrichment in coastal wetlands, particularly in those hydrologically related with the Segura watershed and its irrigation system. In recent years El Hondo and the Mar Menor together make up more than a third of the Spanish wintering population (average 4648 birds). *Podiceps nigricollis* is considered a bird capable of readily exploiting the food resources offered by saline lakes, so it is possible that a similar behaviour occurs in nutrient-enriched brackish or saline wetlands. Whatever the ultimate cause of its increase (e.g. the growing of the breeding population, general eutrophication, etc.), it is obvious that these wetlands play a crucial role in the yearly survival of the population of this grebe (Jehl & Mckernan, 2002; Jehl et al., 2002)

Despite the weak positive response of *Mergus serrator* to the increase in N load, described by the regression model, most local ornithologists regard this species to be in long-term decline. Moreover, the local and national trend for 1991–2000 are both negative, and there are records of more than 400 wintering birds in the 1970s, in counts covering only the northern section of the lagoon (Hernández & Robledano, 1997); these authors suggested that the dredging of the lagoon outlet (Estacio) to create a navigable channel, in 1973, and the subsequent decline in the lagoon fisheries, could have lowered the value of the Mar Menor as a feeding area for the Red-breasted Merganser. The total catch of fish of small species has declined in the long term (from more than 100 tonnes in 1972 to less than 40 tonnes in 2002; data from the local fishermen's associations), A partial recovery occurred during 1986–1996, with catches fluctuating around 60 tonnes per year, coincident with the first phase of nutrient overload, prior to the jellyfish blooms starting in 1995.

It is possible that the trend of *Mergus serrator*, a specialised piscivore, reflects the long term decline of its preferred prey, while the more generalist grebes could have shifted, to a greater extent, to other food types, and the cormorant to other feeding habitats. On the other hand, the parallel decline of both grebes in 1996–1997 and 1999–2000, during a jellyfish-dominated phase, suggest that these species could have experienced a short-term reduction in food resources explaining the poor adjustment to nutrient data.

Food web changes following eutrophication and indicator value of bird species

The alteration of food-web structure, as an indirect response to eutrophication, illustrates the complexity of system responses to changes in nutrient inputs to coastal areas (Cloern, 2001). Food-web changes following nutrient enrichment have been documented elsewhere, with the participation of jellyfish in the control of other trophic levels (Purcell et al., 1999; Arai, 2001; Purcell & Arai, 2001; Sommer et al., 2002;). As indicated above, in the Mar Menor lagoon zooplankton assemblages can be subject to top-down control by the feeding activities of jellyfish (Pérez Ruzafa et al., 2002), which implies that these may play an important role controlling the consequences of eutrophication within the lagoon.

In the study area, the 'jellyfish compartment' could have played a buffering role, during the phase of grebe decline, blocking the transfer of excess nutrients to other compartments (or food items), like fish, benthic invertebrates or other zooplankton. Since both grebes increased again in numbers in 2002–2003, it is possible that the capacity of jellyfish to process nutrients was then overloaded, and new, adequate food sources developed. The isolated peak of Black-necked grebes in 1999 might show an opportunistic response, typical of this species, to rapid peaks in food resources brought about by specific events, such as the flash-flood which occurred at the end of 1997. A similar situation was observed at the end of the seventies (Fig. 6). Grebes may also have shifted – to some extent – their foraging habits during the different phases of the eutrophication process, exploiting alternative sources of food as others (e.g., fish) become scarce.

There is also a possible direct effect of coelenterates on bird prey through the consumption of pelagic fish eggs and larvae, or the competition with zooplanktivorous organisms for food (Purcell & Arai, 2001). As suggested above, the decline and increased year-to-year variability of grebe numbers during the second half of the decade of 1990, could reflect a local shortage of adequate food resources brought by these interactions. This is, in addition, the period when local and national census trends show greater differences (Fig. 7). All these hypotheses need further research.

The role of jellyfish and the effect of recent anthropogenic modifications of the lagoon ecosystem, might reduce the indicator value of bird species, restricting it to some species and to the early and late phases of nutrient increase. However, the initial response of the 'good indicator' species to nutrient increases above threshold values is not negligible, as an 'early warning' signal of uncontrolled environmental changes.

Conclusions

The aggregated dynamic system model constitutes the fist attempt to estimate the overall nutrient load, basically from agricultural areas, entering the Mar Menor lagoon and the associated wetlands complex at a watershed scale, taking into account the socio-economical and environmental driving factors and their evolution. Current loading values, with averages of around 2000 tonnes of nitrogen and 60 tonnes of phosphorus per year, are similar to those found in other intensive agricultural watersheds and agree with the available data regarding the concentration of nutrients in the watercourses and agricultural drainages. The simulation results emphasize the role of heavy rainfall events and floods on the total nutrient load. Future work will be carried out to perform a sensibility analysis of main model parameters and to explore the potential effects of several scenarios regarding land-use change and management options.

Old World studies on lake eutrophication have demonstrated direct and indirect responses of bird populations to changes in water quality (e.g., Nilsson & Nilsson, 1978; Hoyer & Canfield, 1994; Suter, 1994). Also, biotic interactions between primary producers, aquatic invertebrates, fish and birds are gradually becoming better understood and appreciated (Paszkowski & Tonn, 2000). In reviewing the indicator value of birds, species such as the Great Crested Grebe have been mentioned as characteristic eutrophication indicators. The local and global changes in distribution, abundance and breeding behaviour exhibited by this species (Rutschke, 1987; Stanevicius, 2001; Martinoli et al., 2003), are in many cases attributed, at least partially, to changes in the trophic status of wetlands. Our results support the idea that this species and the Black-necked Grebe are the most closely dependant on local trophic conditions, at least during some phases of nutrient increase. The lack of a general bio-indication property regarding the full process of nutrient increase, can then be replaced by an 'early warning' signal value of this species regarding some phases of this process. The Black-necked Grebe dominates the waterbird community of the lagoon (in terms of individuals), but it has a more opportunistic response to changes in food resources, that reduces its value as a general indicator of the process.

The diet and foraging activity of grebes inside the lagoon are poorly known, but the abundance of both species seem to closely track the nitrogen load curve during the early phase of enrichment, suggesting the existence of a direct trophic relationship. In the following phase, jellyfish blooms coincide with bird declines. Jellyfish seem to have a buffering effect that leaves fewer nutrients available to other trophic compartments. In recent years this buffering capacity has probably been overloaded and a fraction of the nutrients released, favouring the growth of new food organisms, is available to the grebes, that respond again numerically. This new phase coincides also with an increase in Coot (*Fulica atra*), a typical phytophagous species of freshwater wetlands, attracted to the lagoon by the dense growth of algal mats around the main seepage and discharge areas.

Unlike grebes, *Mergus serrator*, a typical piscivorous bird, does not seem to be positively affected by eutrophication on the long term, although its suspected decline can respond also to the other various anthropogenic changes affecting the lagoon ecosystem. Since this decline would parallel a long-term reduction in fish catches, the species could be regarded as a potential indicator of habitat and resource deterioration.

The relationships between the net watershed loadings, the trophic state of the Mar Menor lagoon, the role of associated wetlands and the observed changes in aquatic birds will be further investigated through an integrated modelling approach, under which the current aggregated watershed model will be connected with an ecological lagoon model, currently being developed.

The results obtained emphasise the need for an integrated management at the watershed scale of surface, subterranean, transition and coastal waters, as established by the Water Framework Directive, if the sustainable use of coastal lagoons and their high ecological and biodiversity values are to be maintained.

Acknowledgements

This research was supported by the EU funded project DITTY (Development of Information Technology Tools for the Management of European Southern Lagoons under the Influence of River-Basin Runoff, EVK3-CT-2002-00084) in the Energy, Environment and Sustainable Development Programme of the European Commission. We thank the Fundación Séneca (Consejería de Economía, Industria e Innovación, Región de Murcia). We also thank Gustavo A. Ballesteros and Manuel Páez from Consejería de Agricultura, Agua y Medio Ambiente (Murcia Region Environmental Board) for supplying bird data from the Mar Menor wetlands monitoring programme.

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